Originally published for SMAR 2017, fourth International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures, Zurich, Switzerland, 2017.
Final publication is available in the related proceedings, Paper No. 162.

Usefulness of ambient-vibration measurements for seismic assessment of existing structures

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ABSTRACT: A large number of buildings in regions with low to medium seismic hazard have been designed without considering earthquake actions. Retrofitting of all buildings that fail to meet modern code requirements is economically, technically and environmentally unsustainable. Decision-making regarding retrofitting necessity and prioritization is complex. Ambient vibrations are non-destructive and easy to measure, and thus an attractive data source. However, ambient vibrations have very low amplitudes, which potentially lead to sensitivity to testing conditions and stiffness contributions from non-structural elements. Seismic assessment necessitates non-linear behavior extrapolation from linear measurements, which results in biased model predictions. Error-domain model falsification is a data-interpretation methodology that is robust to multi-source uncertainties with unknown and changing correlation values. In this contribution, static non-linear behavior predictions of an existing building in Lausanne, Switzerland, are presented. Ambient-vibration data has been gathered under changing conditions: from undamaged in-service to gradual removal of non-structural elements. Low sensitivity to non-structural elements are found. A numerical model based on the applied-element method is generated and shows potential utility of linear measurements for decision-making using non-linear models involving EDMF under uncertain conditions.

1 INTRODUCTION

A large part of the building stock in regions with low to moderate seismic hazard have been built before thorough seismic considerations have been formulated in building codes. Replacing all buildings that fail comparisons with modern design specifications is impossible from economical, technical and environmental standpoints. Therefore, seismic vulnerability assessment of existing buildings has an important role in prioritizing retrofitting actions. However, assessing seismic vulnerability of existing structures is often complicated by the absence of precise building information such as construction drawings and past structural interventions, and by the large variability of material properties in existing buildings.

Although methodologies exist for rapid assessment at a city-scale level (Lestuzzi et al., 2016), the evaluation of buildings with a high contribution to the resilience of a city, such as hospitals and community centers, may require models with higher fidelity. Also, such physics-based structural models are useful to design targeted and efficient rehabilitation and strengthening.

Model-based structural identification using measurement data is a widespread tool to reduce uncertainty related to model parameter uncertainty. When buildings are analyzed, ambient vibration measurements are a well-suited if not the only available non-destructive data source. Development of economic, sensitive and transportable sensors has led to popularity of ambient-vibration-based structural identification. However, ambient vibrations are strictly limited to linear-elastic behavior. The low amplitudes of vibration, typically 10^{-6} to 10^{-3} m/s^2, do not give insights into non-linear behavior of buildings (Michel et al., 2011). Also, non-structural elements, such as separation walls, doors, windows and heavy furniture, potentially contribute to the building stiffness under very low amplitudes of excitation.

Capacity-based vulnerability estimation of buildings requires non-linear behavior predictions. Therefore, model extrapolation is needed as non-linear behavior differs from exclusively linear behavior under ambient vibrations. A structural identification methodology that explicitly incorporates model uncertainties in a transparent way is used to perform such extrapolation: Error-domain model falsification (EDMF) (Goulet and Smith, 2013; Pasquier and Smith, 2015b).

Through a full-scale case study the usefulness of structural identification using ambient vibration data is assessed. Measurements have been taken on a typical Swiss masonry building in Lausanne for three building states: initial state and after gradual removing of non-structural elements such as windows and stair railings. A complex 3D structural model, using the Applied Element Method (AEM), is used to predict modal properties and non-linear pushover curves of the studied building.

This paper starts with a short description of the methodologies used to perform ambient-vibration-based structural identification using an AEM model. Then, on a full-scale case-study, the reduction in non-linear prediction uncertainty that can be obtained with exclusively linear vibration measurement data is assessed. Finally, next steps and conclusions are discussed.

2 MODEL-BASED MEASUREMENT INTERPRETATION IN A SEISMIC CONTEXT

2.1 Error-Domain Model Falsification

Model-based structural identification is an inverse engineering task that involves ambiguities. Even complex 3D models fail to provide an exact representation of full-scale structures under in-service conditions. Therefore, discrepancies between model predictions and observed behavior are inevitable. As engineering structures are systems, such model errors are spatially correlated to an unknown extent (Goulet and Smith, 2013). Also, for approximate engineering models, uncertainties are rarely zero-mean normal distributions and a limited number of uncertainty sources undermines the applicability of the Central Limit theorem (Pasquier and Smith, 2015a).

EDMF is based on the principle of using measurements to falsify inappropriate model instances instead of optimizing single models. Therefore, measurement and model uncertainties are combined to calculate thresholds $\mathbf{T}$ that bound the domain of acceptance for residuals between model predictions $\mathbf{g}(\boldsymbol{\theta})$ and measured values $\mathbf{y}$ for all N_m measured quantities, according to Eq. (1).

$$\forall i = 1, \dots, N_m \colon\ T_{low,i} \leq g_i(\boldsymbol{\theta}) - y_i \leq T_{high,i} \tag{1}$$

Through the transparent incorporation of uncertainties and the threshold-based reasoning, the applicability of EDMF to tens of full-scale structures and the intuitive understanding by practicing engineers has been shown (Smith, 2016). Also, through avoiding the definition of exact uncertainty distributions and by being insensitive to unknown and changing uncertainty correlations, EDMF results in robust identification and prediction ranges (Pasquier and Smith, 2015b).

In this application to existing buildings, fundamental frequencies derived from ambient vibrations are proposed as a measurement source. Ambient vibrations are a time-efficient and non-destructive measurement source. Measured accelerations are transformed to the frequency domain and analyzed using the Frequency Domain Decomposition technique (Brincker et al., 2001), a popular output-only modal identification technique in civil engineering applications.

EDMF has been used in the past with ambient vibration-based modal properties for linear model identification on bridges (Goulet et al., 2013).

2.2 Applied Element Method

In Switzerland unreinforced masonry buildings make up for the major part of the building stock. Predictions related to the non-linear behavior of masonry, an orthotropic material composed of bricks and mortar joints, remain challenging. In this paper, the AEM is used to predict non-linear pushover curves of a masonry building. AEM is suitable to predict post-yield structural behavior of masonry structures that are defined by a particularly large range of potential failure modes (Garofano and Lestuzzi, 2016; Guragain et al., 2012; Karbassi and Nollet, 2013).

In order to capture failure modes that govern masonry structures, such as rocking, joint de-bonding, sliding or shear diagonal cracking, AEM divides structural components into elements that are connected with springs at element contact points (around the edge). Pairs of normal and shear springs localize stresses, strains and deformations (Meguro and Tagel-Din, 2002). Two types of springs represent masonry behavior: the first type of springs characterizes brick behavior while the second type of springs merges brick-mortar interface and mortar behavior. The behavior of bricks and mortar is assumed to be similar to concrete-type behavior models (Extreme loading® for Structures, 2013). The defined springs are able to capture joint de-bonding, shear sliding, direct tension and partial connectivity between elements. However, shear-compression failure due to high axial loads is not taken into consideration.

3 CASE STUDY: VILLA MARGUERITE, LAUSANNE (SWITZERLAND)

Usefulness of ambient vibration measurements for structural identification is investigated through application to a full-scale masonry building. The Villa Marguerite in Lausanne is a typical Swiss masonry building with 4 floors that has been built in the early 20th century.

Ambient vibrations have been measured on three days, prior to the demolition of the building, using six tri-axial acceleration sensors. The first set of measurements is representative of the initial building state under in-service conditions. The second measurement set has been taken after removal of windows and doors and provisional replacement by wooden panels. The third set of measurements has been taken after all secondary elements, except non-structural walls have been removed. Also, changing atmospheric conditions (temperature and humidity) and solar radiation conditions (changing daytimes) influence the measurement sets (see Table 1).

Results from Frequency Domain Decomposition (FDD) of measurements from the third measurement set are reported in Figure 2. Two fundamental bending modes and one torsional mode can be detected.

The evolution of the fundamental bending frequencies in the two directions is reported in Table 1. Only small changes that do not exceed the levels of measurement uncertainties (sensor sensitivity, cable losses, digitizer-losses and time-domain to frequency-domain transformation are estimated to result in a zero-mean normal distribution with a standard deviation of 0.2 Hz) are observed. Modal characteristics from ambient-vibration measurements are thus insensitive to small changes in atmospheric conditions and non-structural elements such as windows and furniture. As a consequence, ambient vibrations can be measured under in-service conditions.

A physics-based model of the structure is developed using AEM (see Figure 1) with approximatively 26’000 elements connected using 1’900’000 non-linear springs. Although AEM allows high-fidelity representation of the structural system, some assumptions are inevitable at the modelling stage: soil-structure interaction is ignored as the base is modelled to have fixed supports; non-bearing separation walls are omitted; and the slab and roof structure are idealized to be isotropic elements with an equivalent stiffness and an equivalent density that include non-structural covering.

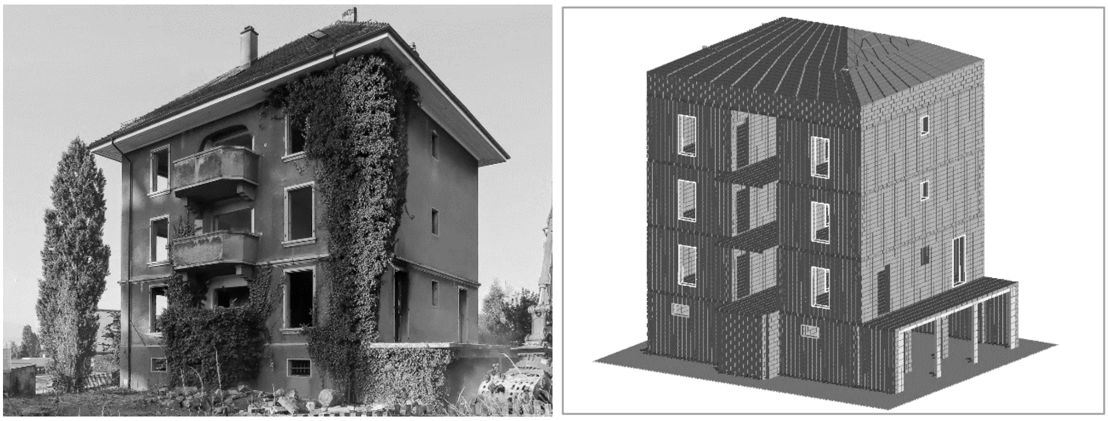

Figure 1. Figure of the Villa Marguerite, Lausanne (Photo Credit IMAC EPFL) and view of the AEM model of the Building.

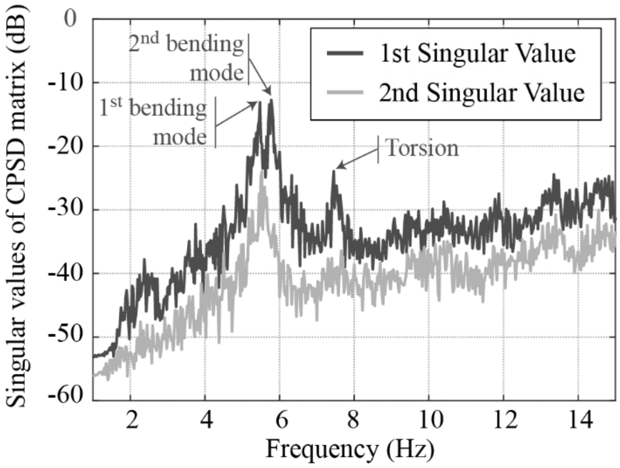

Figure 2. Spectral analysis of vibration measurement on the building. Singular values are calculated from the Correlation Power Spectral Density (CPSD) matrix to identify global structural modes.

Nine parameters are estimated to have an influence on the linear and non-linear model predictions (see Table 2). Slab parameters (density and stiffness), equivalent roof stiffness and brick parameters are assumed to have an influence on linear and non-linear behaviour predictions of the structure, while mortar properties (compressive and tensile strength, friction coefficient and separation strain) mainly govern the predicted non-linear behavior range. Initial parameter ranges are derived using engineering judgement and existing literature.

In order to bypass important simulation time and guided by the needs of a preliminary model class evaluation, a Box-Behnken sampling scheme is used. Thus, a total of 121 parameter combinations sampled from initial parameter ranges shown in Table 2 are simulated. The Box-Behnken design divides the initial parameter ranges by picking extreme points of the range as well as the center point. In cases where a thorough structural identification of all the parameters is useful, the 121 parameter combinations can be used to derive a surrogate model.

Table 1. Natural frequency derived from ambient vibration measurements for changing building states defined by gradual removal of non-structural elements. Changing environmental conditions and non-structural elements have little influence on observed natural frequencies.

Building state	Date of measurement	Longitudinal fundamental frequency [Hz]	Transversal fundamental frequency [Hz]
Initial	26th June, 2015 (midday)	5.7	5.8
After removal of some secondary elements	14th July, 2015 (evening)	5.7 (-)	5.7 (-2%)
After removal of all secondary elements (except separation walls)	15th July, 2015 (morning)	5.5 (-3.5%)	5.8 (-)

Table 2. Initial and identified parameter ranges for chosen material properties of the structural model. Parameter identification reduces the range of linear parameters only.

Material property	Units	Initial range	Identified values
Young's modulus of bricks	kN/mm^2	50 – 1000	50
Poisson's coefficient of bricks	-	0.1 – 0.3	0.1– 0.3
Young's modulus slab	kN/mm^2	750 – 2500	750 – 1625
Density slab	t/m^3	2.0 – 4.5	3.25 – 4.5
Tensile Strength of Mortar	N/mm^2	0.5 – 2.5	0.5 – 2.5
Compressive Strength of Mortar	N/mm^2	5.0 – 20.0	5.0 – 20.0
Friction Coefficient of Mortar	-	0.55 – 0.95	0.55 – 0.95
Separation Strain of Mortar	-	0.05 – 0.15	0.05 – 0.15
Young's modulus roof	kN/mm^2	500 – 1500	1000 – 1500

In addition to the measurement error N(0,0.2Hz), three sources of model uncertainties are identified: model error due to element size and secondary parameters (uniform between -7.5% and +7.5%); omission of non-structural walls (with a thickness below 10 cm) and irregular boundary conditions as well as simplification of the roof structure (between -10% and 10%); and omission of soil-structure interaction by idealizing fixed boundary conditions (-15% to 0%). According to Eq. (2), a negative model error, ε_{model}, corresponds to a model that results in overestimating structural responses. Given boundary conditions cannot be stiffer than fixed, the uncertainty is biased towards overestimated frequencies. EDMF allows engineers to define such biased uncertainties.

$$Truth = g(\boldsymbol{\theta}) + \varepsilon_{model} \qquad (2)$$

Frequencies that are predicted using the AEM model (see Fig. 1) are reported in Figure 3 for the bending modes alongside measured frequencies and EDMF thresholds. Compared to the measured frequency, the frequency predictions are shown to be overestimated. This observation is in agreement with the biased model uncertainty estimation.

Unsurprisingly, the reduction in parametric uncertainty that is achieved using linear measurements is restricted to linear material properties. As can be seen in Table 1, the highest reduction in parametric uncertainty is achieved for Young's modulus of masonry bricks. As a Box Behnken design is used to sample the parameter space, an upper limit of potential parameter identification using EDMF is obtained.

Based on the AEM model (see Fig. 1), which has been employed to predict natural frequencies, non-linear transversal push-over curves are predicted. A linearly increasing displacement distribution along the building elevation is used to derive pushover curves. Predicted base shear as a function of displacement of the upper slab is reported in Figure 4.

Through a reduction in the parametric uncertainty related to linear material properties (see Table 1), non-linear prediction uncertainty is reduced. Although predictions of the maximum force that the building can sustain remain scattered, the displacement capacity of the building is predicted with higher precision. This is an encouraging finding for structural identification of non-linear structures with linear measurement data.

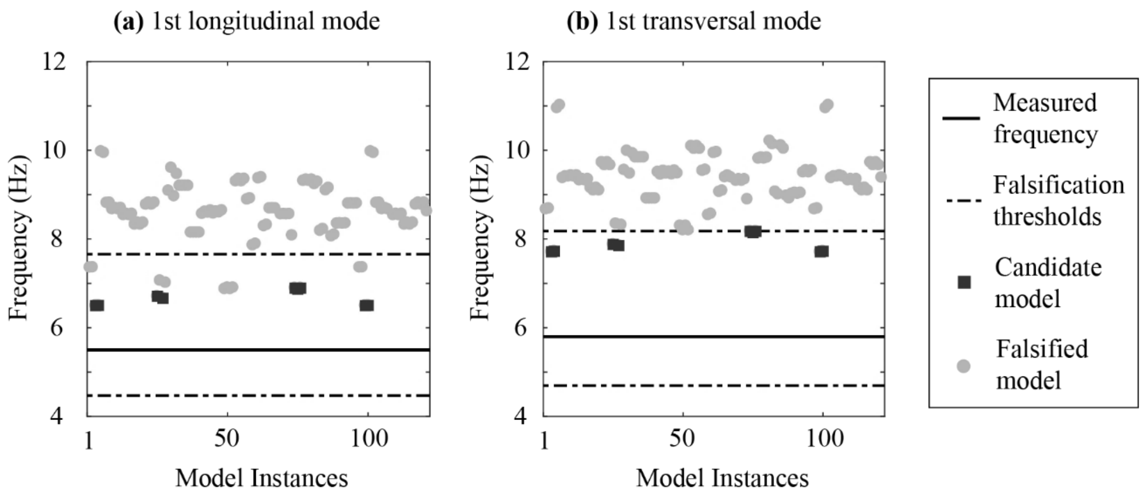

Figure 3. Predicted frequencies related to the fundamental bending modes in the longitudinal and transversal direction. Predictions are biased with regard to the measured frequencies.

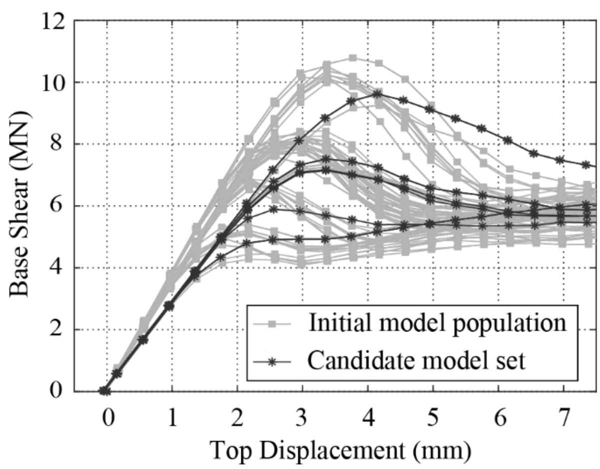

Figure 4. Predicted push-over curves in the transversal direction. Prediction uncertainty can be reduced, however the prediction range resulting from candidate models remains large.

4 DISCUSSION AND OUTLOOK

Comparison between model predictions and measured behavior shows a systematic overestimation of natural frequencies. Model assumptions such as fixed boundary conditions lead to overestimated results. Future work includes estimating the influence of non-fixed boundary conditions (soil-structure interaction) on the predicted natural frequencies in order to reduce the combined uncertainty. EDMF allows the engineer to gradually include knowledge and increase model fidelity by adapting uncertainties in a transparent way.

In such a perspective of gradual knowledge acquisition, tensile strength of mortar has the highest influence on candidate pushover curve predictions. Therefore, further reduction in the prediction of maximum base shear necessitates knowledge acquisition regarding mortar tensile strength. However, current technology requires laboratory tests to deduce material strength.

Surrogate models are needed to perform a thorough identification of parameter values, which is an important step if, for instance, retrofitting is to be designed. A low number of samples has been used for the Latin Hypercube Sampling in order to get a first evaluation of the model class and the capacity to reduce parametric prediction uncertainty in the non-linear range.

If predictions that involve extrapolation are performed, the prediction uncertainty differs from the identification uncertainty. An exact quantification of prediction uncertainty is needed to provide the decision-maker with robust prediction ranges.

The non-linear predictions that are used to verify the usefulness of linear measurements for non-linear parameter identification are static non-linear pushover curves. In case dynamic non-linear time histories are predicted, the uncertainty reduction might be more important, given the influence of the fundamental modes on dynamic building behavior.

5 CONCLUSIONS

Structural identification of non-linear behavior models using linear measurements is presented. The following conclusions are drawn from the application of vulnerability predictions using a non-linear AEM model and linear vibration measurements:

- Although ambient vibration measurements are characterized by low amplitudes, low sensitivity to non-structural elements such as windows and furniture is observed. This is an essential feature for robust model identification using physics-based models.
- Reducing the parametric uncertainty of linear properties can reduce the behavior uncertainty in the non-linear range. Additional case studies are needed to confirm this finding. In addition, the costs of measurement acquisition and especially of complex non-linear structural models may not justify the application of the methodology in cases for which the reduction in prediction uncertainty is low.
- EDMF allows the engineer to combine various uncertainty sources in a transparent and intuitive way. In addition, in presence of scarce numbers of measurements and model predictions, EDMF helps to indicate subsequent steps to take.

6 ACKNOLEDGMENTS

This work was funded by the Swiss National Science Foundation under Contract No. 200020-169026. Costs of the measurement system were partially covered by the Swiss National Science Foundation under grant No. 150785. The authors thank the Real Estate and Infrastructures Department of EPFL for the access to the building and A. Herzog for documenting the tests.

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